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Acoustic Treatment Design Scaling Methods

Volume 1: Overview, Results, and Recommendations

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Summary

Scale model fan rigs that simulate new generation ultra-high-bypass engines at about 1/5 scale are achieving increased importance as development vehicles for the design of low noise aircraft engines. Testing at small scale allows the tests to be performed in existing anechoic wind tunnels, which provides an accurate simulation of the important effects of aircraft forward motion on the noise generation. The ability to design, build, and test miniaturized acoustic treatment panels on scale model fan rigs representative of the full scale engine provides not only a cost-saving but an opportunity to optimize the treatment by allowing tests of different designs. A scale model treatment test may cost from $150K to $250K, while an equivalent full scale engine test may require $1M or more.

The primary objective of this study is to develop methods that will allow scale model fan rigs to be successfully used as acoustic treatment design tools. The study focuses on finding methods to extend the upper limit of the frequency range of impedance prediction models and acoustic impedance measurement methods for sub-scale treatment liner designs, and confirm the predictions by correlation with measured data. This phase of the program had as a goal doubling the upper limit of impedance measurement from 6kHz to 12kHz. The program utilizes combined analytical and experimental methods to achieve the objectives. Ultimately, impedance measurements up to 50 kHz. will be required.

Analytical impedance models were developed to provide a theoretical basis for understanding flow phenomena pertinent to the behavior of treatment panel designs at small scales and the significant differences from full-scale behavior. Laboratory testing conducted included normal incidence impedance measurements, DC flow resistance measurements, and in-duct transmission loss measurements. In some cases, the testing has proven to be inadequate for treatment scaling purposes. The goal of increasing the upper frequency measurement limit for acoustic impedance to above 12,000 Hz. was achieved in the case of no grazing flow, but attempts to measure impedance at high frequencies in the presence of grazing flow were unsuccessful. Analytical impedance prediction models were developed that show excellent correlation with the measured normal incidence impedance beyond the 12,000 Hz. goal, up to about 13,000 Hz.

A set of guidelines for the utilization of scale model treatment as a full scale engine treatment design tool was established. A procedure for incorporating sub-scale treatment effects into the treatment design optimization was proposed.

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1. Introduction

1.1 Background

The noise suppression provided by acoustic treatment liners in aircraft engine ducts is essential to being able to meet aircraft flyover noise regulations. Testing to validate the performance of acoustic treatment design concepts is an integral part of the suppression system design process. The cost of building and testing treatment designs on full scale engines, however, is prohibitive, and designers are seldom afforded the luxury of more than one attempt at designing and testing the final design that will be used in production.

Scale model fan rigs that simulate new generation ultra-high-bypass engines at about 1/5 scale are achieving increased importance as development vehicles for the design of low noise aircraft engines. Testing at small scale allows the tests to be performed in existing anechoic wind tunnels, which provides an accurate simulation of the important effects of aircraft forward motion on the noise generation. The ability to design, build, and test miniaturized acoustic treatment panels on scale model fan rigs representative of the full scale engine provides not only a cost-saving but an opportunity to optimize the treatment by allowing tests of different designs. To be able to use scale model treatment as a full scale design tool, it is necessary that the designer be able to translate the scale model design and performance to an equivalent full scale design with confidence.

The GEAE Universal Propulsion Simulator (UPS), shown in cross-section in Figure 1, is a typical scale model fan rig[1]. The model has the capability of incorporating treatment panels in the inlet duct, fan frame area, and exhaust duct. The treatment is accommodated by removable panels, minimizing hardware cost and configuration change time.

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1 Balan, C. and Hoff, G. E., "Turbofan Propulsion Simulator", Aerospace Engineering, August, 1993, pp. 11-16.

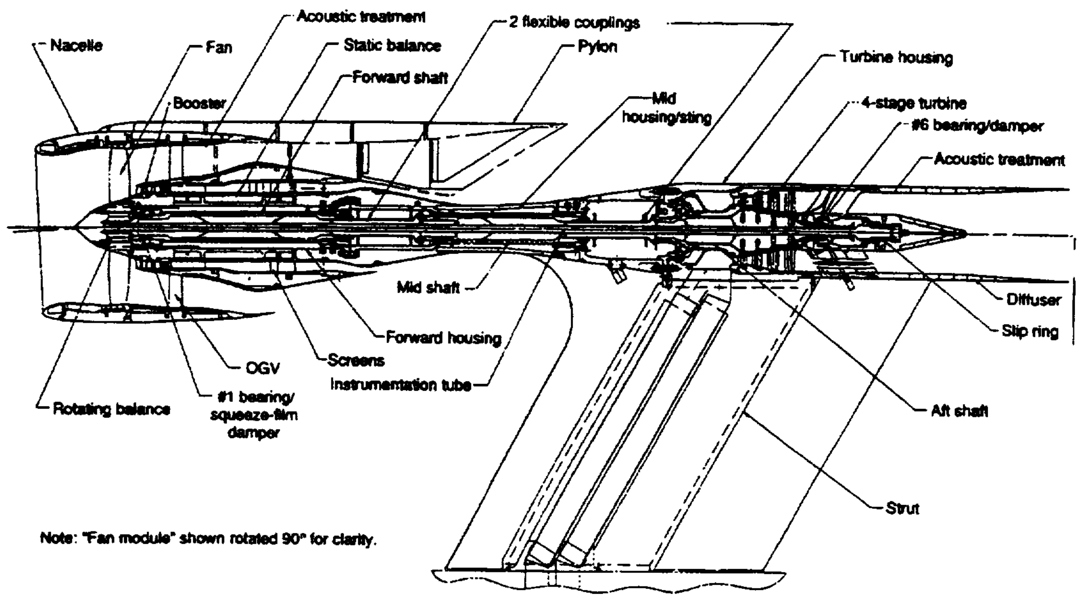

Figure 1. Schematic of UPS Scale Model Fan Simulator layout

The key to being able to use sub-scale acoustic treatment results for design and development of full scale liners is the acoustic treatment impedance parameter. Theoretically, the suppression obtained at a full scale frequency for a given treatment impedance value should be the same as that obtained with the same impedance value at the corresponding scaled frequency in the scale model. At that frequency, at least, the impedance design parameter transfers directly from sub-scale to full scale.

When testing acoustic treatment on sub-scale model vehicles, it would be desirable to achieve the same treatment suppression as a function of scaled frequency that would be obtained on the full scale engine. This requires that the source generation characteristics, the engine geometry, and the acoustic impedance scale directly with frequency over the full frequency range of interest. Although sub-scale fan rigs are believed to represent the source characteristics and duct geometry with adequate validity, the treatment impedance representation presents unique problems.

The acoustic impedance for conventionally designed acoustic treatment panels does not scale directly with geometric length and frequency, due to second-order effects. One cannot simply geometrically "shrink" a full scale treatment design and expect the impedance at the scaled frequency to be the same as that at full scale. While the sub-scale treatment can be designed to achieve any impedance at a single frequency, it may not have the same impedance spectrum over the scaled frequency range as the equivalent full scale liner does over its corresponding range.

Thus, the particular impedance characteristics of the sub-scale liner under its particular operating conditions must be accommodated for treatment scaling to be a successful design tool. The key is being able to know what acoustic impedance has been obtained as a function of frequency in the scale model with sufficient assurance that the impedance values can be transferred to the full scale design, if not the physical treatment design parameters. To achieve this, improved impedance models and measurement methods are needed to be able to determine acoustic impedance accurately at high frequencies. For a more complete discussion of the relation and importance of impedance to treatment scaling, see Volumes 2 and 3 of this Final Report.

1.2 Objectives and Approach

The primary objective of this program was to develop methods that will allow scale model fan rigs to be successfully used as acoustic treatment design tools. The program focused on finding methods to extend the upper limit of the frequency range of impedance prediction models and acoustic impedance measurement methods for sub-scale treatment liner designs The upper limit of impedance measurement for full scale treatment panels has, in the past, been in the range of 6000 Hz. It is the objective of this study to double that limit to above 12,000 Hz., for liner impedances both with and without the effects of grazing flow.

Elements of the program aimed at evaluating the feasibility, problems, and methods of treatment scaling were the following:

1. Extend existing analytical treatment impedance models to account for high frequency effects.
2. Perform laboratory tests on a variety of treatment panels built at three different scales (1:1, 1:2, and 1:5) to identify high frequency measurement problems and provide a database for the evaluation of scaling effects.
3. Use the measured results to validate theoretical impedance models and evaluate the magnitude of scaling effects.
4. Develop recommendations for improved methods of measuring treatment impedance at high frequencies for future development.
5. Develop a recommended procedure for the use of scaled treatment in the design optimization of treatment for full scale fans.

Analytical impedance models were developed to provide a theoretical basis for understanding flow phenomena pertinent to the behavior of treatment panel designs at small scales and the significant differences from full-scale behavior. Improvements were made to existing liner impedance models to predict sub-scale effects more accurately. Impedance models were examined and reformulated to account for effects that vary with nondimensional scaling parameters such as orifice/pore diameter based acoustic Reynolds number, orifice discharge coefficients, boundary layer thickness to orifice diameter ratios, reduced frequency, etc. These studies were primarily limited to perforated sheets, including micro-porous, and woven mesh sheets. Bulk absorbers are also of interest, but time and cost limitations prevented in-depth examination of these materials.

Laboratory testing included the following measurements:

1. Normal incidence impedance tube testing (no grazing flow) with three impedance tube sizes (10 cm., 3 cm., and 1.5 cm.), to measure impedance up to 13,000 Hz.
2. DC flow resistance testing at room temperature.
3. DC flow resistance testing at high temperatures, up to 1000 degF.
4. In-duct DC flow resistance testing in the presence of grazing flow, up to Mach 0.8.
5. In-duct measurements of transmission loss in the presence of grazing flow up to Mach 0.8, using modal measurements.

Although much useful data for the evaluation of treatment scaling was acquired, not all laboratory testing was successful, as will be discussed below.

2. Executive Summary of Results

Extensive studies of effects of high frequencies and small scales on acoustic treatment panels have been completed. An extended frequency impedance prediction model has been developed and coded into FORTRAN. Work was started on the development of a time-domain model for nonlinear effects on the impedance of a single-degree-of-freedom (SDOF) resonator covered by a perforated sheet. Effects were identified that may result in improved accuracy for full scale impedance models.

The goal of increasing the upper frequency measurement limit for acoustic impedance to above 12,000 Hz. was achieved in the case of no grazing flow, but attempts to measure impedance at high frequencies in the presence of grazing flow were unsuccessful. Analytical impedance prediction models have been developed that show excellent correlation with the measured normal incidence impedance up to about 13,000 Hz. Measurements up to 12,000 Hz. can be accomplished in the 1.5 cm tube, but require. extra care in preparing the treatment samples. The honeycomb cell cross-dimensions, for example, must be scaled to half size to maintain local reaction at 12,000 Hz.

Measurements of DC flow resistance at high temperatures indicate a simple and reliable temperature conversion based on the temperature-dependence of viscosity can be reliably applied to perforates and wiremesh materials. Measurements of DC flow resistance with grazing flow show expected behavior from perforate and wiremesh materials. Time did not allow more detailed analytical correlation of the DC flow measurement with grazing flow data.

In-duct measurements of acoustic impedance with grazing flow using the two-microphone method were unsuccessful. This was attributed primarily to defects in the instrumented duct test samples used for the measurement, caused by difficulties in fabrication. Alternative procedures for sample preparation are suggested to improve this method, and it is generally concluded that the precision requirements to successfully apply this method are very stringent.

In-duct transmission loss measurements, with and without grazing flow, met with limited success. The measurements were performed up to Mach 0.8, but difficulty was encountered in attempting to correlate the analytical prediction with the measured data with what would be considered to be adequate agreement. The difficulties are most likely to be attributable to measurement problems in the calibration of the multiple microphone arrays used in the modal decomposition.

A set of guidelines for the utilization of scale model treatment testing as a full scale engine treatment design tool was recommended. The key to being able to use treatment scaling is the ability to predict and measure acoustic impedance for sub-scale panels accurately up to the highest scaled frequency required. This will require using the simplest possible panel designs (a wire-mesh facesheet SDOF panel is recommended), and being able to reliably predict and measure the panel impedance.

3. Guide to Other Report Volumes

3.1 Volume 2 - Advanced Treatment Impedance Models for High Frequency Ranges

Volume 2 documents the results of the development of improved models for the acoustic impedance of treatment panels at high frequencies, for application to sub-scale treatment designs. Effects that cause significant deviation of the impedance from simple geometric scaling are examined in detail, an improved high frequency impedance model is developed, and the improved model is correlated with high frequency impedance measurements.

Only single-degree-of-freedom honeycomb sandwich resonator panels with either perforated sheet or "linear" wiremesh faceplates were considered here. The objective was to understand those effects that cause the simple single-degree-of-freedom resonator panels to deviate at the higher scaled frequency from the impedance that would be obtained at the corresponding full scale frequency. This would allow the sub-scale panel to be designed to achieve a specified impedance spectrum over at least a limited range of frequencies. As long as the impedance achieved in the scale model is known with a sufficient degree of accuracy, it can be reliably translated to the full scale design.

An advanced impedance prediction model was developed that accounts for some of the known effects at high frequency that have previously been ignored as a small source of error for full scale frequency ranges. The model was implemented in a computer program and used to compare with predicted data from the currently-used impedance model and with measured data for a number of treatment configurations of various scale. Based on this study, the outlook on ability to use scaled perforate facesheet single-degree-of-freedom resonator liners to represent full scale is encouraging, but care must be taken to make the proper adjustments in porosity and cavity depth of the scaled liner to best fit the full scale impedance.

3.2 Volume 3 - Test Plans, Hardware, Results, and Evaluation

Volume 3 documents the results of laboratory tests to evaluate liner acoustic properties and validate advanced treatment impedance models. These laboratory tests included DC flow resistance measurements, normal incidence impedance measurements, DC flow and impedance measurements in the presence of grazing flow, and in-duct liner attenuation as well as modal measurements. Test panels were fabricated at three different scale factors (i.e., full-scale, half-scale, and one-fifth scale) to support laboratory acoustic testing. The panel configurations include single degree of freedom (SDOF) perforated sandwich panels, SDOF linear (wire mesh) liners, and double degree of freedom (DDOF) linear acoustic panels.

Six sets of acoustic test samples with fifteen liner configurations and three scale factors were fabricated and tested. The DC flow resistance measurements and normal incidence impedance tests provided useful data to support scale treatment impedance analytical model development and validation. The analyses demonstrated that the theoretical impedance models discussed can be upgraded and modified using suitable analytical assumptions and empirical adjustments to fit both full-scale and sub-scale liners requirements.

Two-degree-of-freedom liner mathematical models have been discussed briefly in this volume. The analyses indicate that model improvements applied to SDOF liners can be applied in appropriate fashion to DDOF liners.

3.3 Volume 4. - Numerical Simulation of the Nonlinear Acoustic Impedance of a Perforated Plate Single-Degree-of-Freedom Resonator Using a Time-Domain Finite Difference Method

Volume 4 documents the results of the development of a numerical simulation model of the nonlinear acoustic impedance of a perforated plate single-degree-of-freedom resonator using a time-domain, finite difference approach. Single-degree-of-freedom resonators consisting of honeycomb cells covered by perforated facesheets are widely used as acoustic noise suppression liners in aircraft engine ducts. The acoustic resistance and mass reactance of such liners are known to vary with the intensity of the sound incident upon the panel. Since the pressure drop across a perforated liner facesheet increases quadratically with the flow velocity through the facesheet, this is known as the nonlinear resistance effect.

In the past, two different empirical frequency domain models have been used to predict the Sound Pressure Level effect of the incident wave on the perforated liner impedance, one that uses the incident particle velocity in isolated narrowbands, and one that models the particle velocity as the overall velocity. In the absence of grazing flow, neither frequency domain model is entirely accurate in predicting the nonlinear effect that is measured for typical perforated sheets.

The time domain model was developed to understand and improve the model for the effect of spectral shape and amplitude of multi-frequency incident sound pressure on the liner impedance. This is of particular concern with regard to frequency-scaling of acoustic treatment, since the possibility exists that the nonlinear resistance and mass reactance effects may be significant compared to the grazing flow effects at high frequencies. A computer code for the time-domain finite difference model was developed and predictions using the models were compared to current frequency-domain models.

3.4 Volume 5 - Analytical and Experimental Data Correlation

Volume 5 documents the results and data analysis of the in-duct transmission loss measurements that were taken in the GEAE Acoustic Laboratory and analyzed by Rohr, Inc. Transmission loss testing was performed on full scale, 1/2 scale, and 1/5 scale treatment panel samples. The objective of the study was to compare predicted and measured transmission loss for full scale and sub-scale panels in an attempt to evaluate the variations in suppression between full and sub-scale panels which were ostensibly of equivalent design. A computer program was written to solve for the forward and backward mode coefficients of acoustic propagation in a rectangular duct based on pressure measurements in hardwall sections of the duct.

Modal measurement data taken at GEAE were transferred to Rohr, Inc, for analytical evaluation. Using a modal analysis duct propagation prediction program, Rohr compared the measured and predicted mode content. Generally, the results indicate an unsatisfactory agreement between measurement and prediction, even for full scale. This was felt to be attributable to difficulties encountered in obtaining sufficiently accurate test results, even with extraordinary care in calibrating the instrumentation and performing the test. Test difficulties precluded the ability to make measurements at frequencies high enough to be representative of sub-scale liners.

It was concluded that transmission loss measurements without ducts and data acquisition facilities specifically designed to operate with the precision and complexity required for high sub-scale frequency ranges are inadequate for evaluation of sub-scale treatment effects. If this approach is to be pursued further, it will be necessary to develop adequate sub-scale laboratory test facilities and provide instrumentation of sufficient precision and complexity.

4. Testing Problems Encountered

4.1 DC Flow Resistance Measurement with Grazing Flow

Measurements of DC flow resistance with grazing flow for three out of the four instrumented treatment samples show expected behavior, but obvious discrepancies were encountered in measurements of one of the samples. The most likely source of the measurement problem is thought to be an inadequate seal between the facesheet and the walls of the DC flow duct insert at the back of the panel.

The problem is indicative of the level of care that must be taken in sample preparation, even when the fabrication is accomplished by experts. One possible cure would be to prepare multiple samples, both to guarantee that at least one has no defects and to provide some data on statistical variation of the samples and the measurement. Unfortunately, time did not allow more detailed analytical correlation of the DC flow measurement with grazing flow data, which may have provided further indication of the nature of the measurement problem.

4.2 In-Situ Impedance Measurement with Grazing Flow

In-duct measurements of acoustic impedance with grazing flow using the two-microphone method were unsuccessful. This was attributed primarily to defects in the instrumented duct test samples used for the measurement, caused by difficulties in instrumentation, construction, and fabrication. This occurred in spite of extraordinary measures taken to insure the best procedures were followed in order to avoid exactly these types of problems.

Test panels were instrumented by selecting an individual hexcell, which was visible due to the use of a plexiglass backplate, and drilling holes into the cavity through the backplate in order to mount the two microphones. Extreme care was used in the location and preparation of the mounting holes. Extreme care was used in the installation and location of the microphones.

It was not possible to guarantee that the edge of the honeycomb of any individual cell was perfectly bonded and sealed to the faceplate. The choice of the cell was simply by locating the instrumented cell in a desired area of the treatment panel surface. Although slight defects in bonding are insignificant as far as the overall performance of the treatment in normal use, even slight defects in the seal appear to have a large effect on the use of that cavity for the two-microphone measurement. Only one hexcell cavity in each treatment panel sample was instrumented—it appears that the wrong cell was chosen four times.

Although alternative procedures for sample preparation are suggested to improve this method (see Volume 5 of the Final Report), it is generally concluded that the precision requirements of the in-situ two-microphone method are so stringent that the likelihood of applying the method successfully, especially at higher frequencies and smaller scales, is very small.

4.3 In Duct Transmission Loss Measurements

In-duct transmission loss measurements, with and without grazing flow, met with limited success. The measurements were performed up to Mach 0.8, but difficulty was encountered in attempting to correlate the analytical prediction with the measured data with what would be considered to be adequate agreement (see Final Report Volume 5). The difficulties are most likely to be attributable to measurement problems in the calibration of the multiple microphone arrays used in the modal decomposition.

A successful in-duct transmission loss measurement will require a higher level of precision in duct apparatus and instrumentation than that currently obtainable in a typical industrial acoustics laboratory. In order to achieve the high frequencies typical of scaled treatment, it will be necessary to design and fabricate highly precise miniature flow ducts, develop the craft of fabricating sub-scale treatment samples for the duct application, and develop complex miniaturized transducer arrays that function with adequate magnitude and phase calibration over the higher frequency range.

The cost of developing such a facility would have to be justified by the contribution of the measurements to the development of improved correlations between predicted and measured impedances for sub-scale treatment designs. The facility would be specialized to sub-scale treatment purposes, and would have little use for full scale treatment designs. Additionally, specialized training may be required for technicians in order to perform the experiments with the required attention to detail and precision.

5. Recommended Treatment Scaling Procedures

5.1 Impedance-Based Treatment Design

Based on the various successes and difficulties encountered in this program, the following set of guidelines is recommended regarding the use of sub-scale treatment in scale model fan vehicles as a tool for treatment design for full scale fans:

- The fundamental design parameter for the treatment is the acoustic impedance. The objective is to obtain the same impedance in the sub-scale duct as in the full scale duct at corresponding sub-scale and full scale frequencies.
- It is critical to know the impedance of the liner in the sub-scale duct at each frequency of interest with sufficient accuracy to be useful for design. This requires reliable and accurate methods of predicting and/or measuring acoustic impedance under fan duct operating conditions up to the highest scaled frequency needed for design over the full scale frequency range.
- It appears to be impossible to design a sub-scale treatment panel that simulates the impedance of a desired full scale treatment panel over the full range of sub-scale frequencies. Therefore, the simplest possible (easiest to manufacture) design for a sub-scale panel should be used to provide known impedances over a limited frequency range. This may require multiple configurations of sub-scale panels to obtain sufficient design information to cover the full frequency range.
- The simplest sub-scale treatment panel design for which impedance is predictable up to reasonably high frequencies, at present, is a linear wiremesh bonded directly to honeycomb core (no supporting perforate sheet) SDOF sandwich construction. It would be advisable to use a scaled wire diameter for the mesh and use as small a honeycomb cell cross dimension as possible. A perforate facesheet scaled both in hole diameter and thickness would be the second choice. Uniform ceramic foam bulk absorbers hold some hope for the future.

At present, acoustic impedance of sub-scale liners can be measured accurately up to 13,000 Hz. in the 1.5 cm. normal incidence impedance tube. This, however, does not account for grazing flow effects. Since the linear wiremesh facesheet is known to be less affected by grazing flow, it would be a better choice at present than a sub-scale perforate. Further work is needed to extend the upper limit of impedance measurement frequency and find methods to measure at high frequencies in the presence of grazing flow.

5.2 Treatment Design Optimization

Optimization of acoustic treatment designs for full scale engines using scale model treatment tests as a tool requires only slight modifications from conventional design procedures. The primary difference is the insertion of a scaled treatment test program into the design procedure between the preliminary design stage and the final confirmation of design by full scale engine test.

Figure 2 is a flow chart of the proposed treatment design optimization process, including scaled treatment tests. It is assumed that the preliminary design is determined by use of an analytical prediction procedure such as modal analysis, but the preliminary design could also be based on standard design practices or previous experience (that is, empirical databases). The process also assumes the existence of fully validated treatment scaling design methods. The function of the scaled treatment testing would be to confirm the preliminary treatment design prior to committing it to full scale fabrication and test.

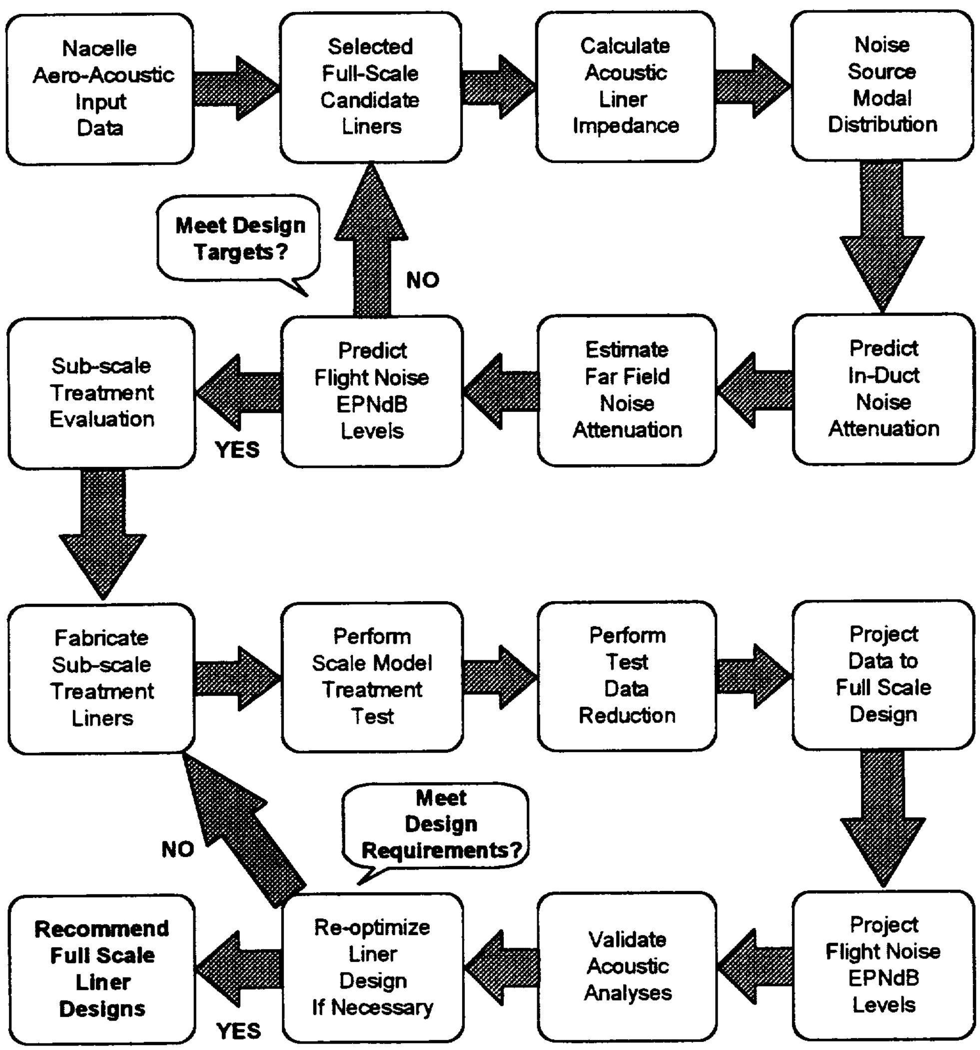

Figure 2. Flow chart for treatment design optimization process utilizing treatment scaling.

6. Proposed Impedance Measurement Methods

6.1 Objectives

Innovative methods are needed for measuring the impedance of sub-scale treatment panels up to frequencies on the order of 50,000 Hz. The measurement must include broadband, high intensity acoustic excitation and the effects of grazing flow. Without reliable impedance measurement methods, it will not be possible to use treatment scaling as a design tool.

6.2 Sub-Miniature Normal Incidence Impedance Tube

One approach is the further miniaturization of the normal incidence impedance tube. Among the problems faced in reducing the diameter of the impedance tube are that the surface of the sample becomes extremely small and that viscosity effects on propagation in the tube become more important. Several proposals have been offered to overcome these limitations.

One way to increase the upper frequency limit of the tube is to measure or account for higher mode propagation in the tube. This could be done for either a circular or square cross-section tube with appropriate miniaturized instrumentation. The use of multiple transducers magnifies the transducer calibration problem. Multiple axial channels could be used to produce a number of sample surfaces simultaneously, but each channel would have to be instrumented separately.

This method could be used to measure effects of high intensity broadband sound, but cannot account for the effects of grazing flow. Special high frequency sound sources would be required.

6.3 Miniature Flow Duct

This proposal would entail a miniaturization of the duct propagation method of measuring impedance as proposed by Watson, Jones, Tanner, and Parrott[2]. The size of the duct would be scaled down such that one mode is cut on at the highest frequency of interest. Figure 3 is an illustration of the flow duct apparatus.

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2 Watson, W. R., Jones, M. G., Tanner, S. E., and Parrott, T. L., "A Finite Element Propagation Model for Extracting Normal Incidence Impedance in Nonprogressive Acoustic Wave Fields", NASA TMX-110160, 1995.

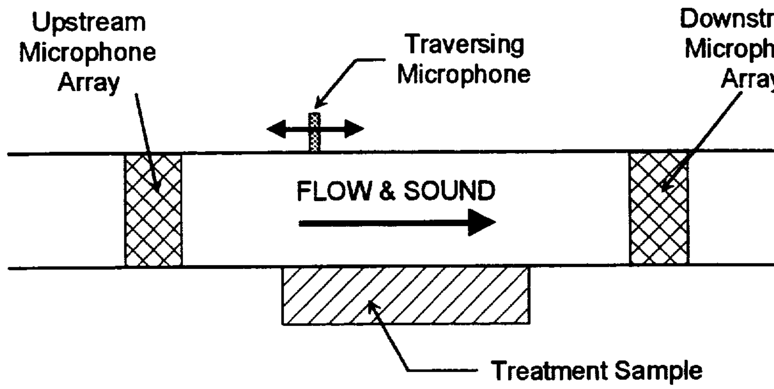

Figure 3. Diagram of proposed flow duct method of impedance measurement, showing alternative traversing microphone and upstream and downstream microphone arrays.

The method could be extended to allow and measure several higher order modes, which could further increase the upper frequency limit. Discriminating multiple modes would require upstream and downstream microphone arrays (shown as an alternative microphone system in Figure 3), which would, however, greatly complicate the measurement and require a high level of carefulness in its performance.

For the modal measurement method with higher order modes, a least squares fit to the modal data could be used iteratively to provide estimates of the treatment impedance. An initial estimate of the treatment impedance could be determined analytically, and, using the modes determined from the modal measurement as propagating *into* the test section (downstream-propagating modes at upstream end and upstream-propagating modes at downstream end), the modes propagating *out of* the test section could be predicted.

The predicted out-going modes could be compared to the measured out-going modes to determine an overall variance (sum of squares of the differences). The impedance could then be varied in the complex plane to attempt to obtain a least squares fit to the modal differences. A number of numerical procedures, such as the conjugate-gradient method[3], could be used to automate the least squares iteration.

This method would have the advantage of including the effects of grazing flow. Since the duct would have a small cross sectional area, high flow rates could be obtained with moderate weight flow capabilities. The analysis may have to account for acoustic propagation in non-uniform flow, which would require measurement of the flow profile at several stations along the test section.

[3] Stoer, J. and Bulirsch, R., *Introduction to Numerical Analysis*, Springer-Verlag, 1992, Chapter 8.

6.4 Free Field Surface Reflection Methods

Numerous authors have examined methods to measure impedance of surfaces using one or more microphones located above the surface in the infinite half-space[4,5,6]. The method was developed primarily to measure the impedance of the ground for outdoor sound propagation analyses. Sound sources considered either generated spherical waves from point sources or used point sources located sufficiently distant that the incident waves could be considered to be plane waves.

Data analysis consists of determining FFT's of the signals measured by precisely-located microphones, converting the FFT's to either cross-spectra or transfer functions, and relating the measured signals to the theory of wave reflection from an impedance boundary into an infinite half-space. The area of the impedance surface is usually assumed to be large enough that edge effects can be neglected. Figure 4 is a schematic of the measurement setup.

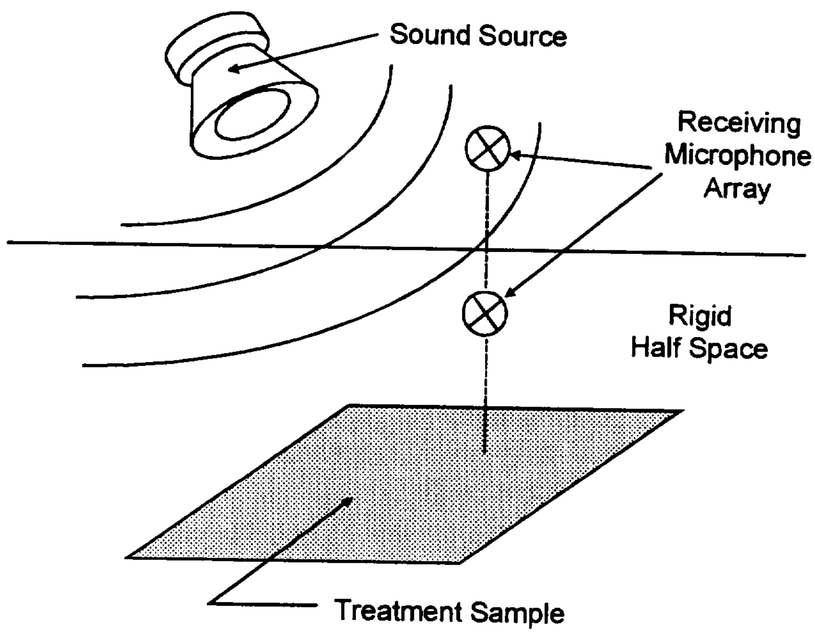

Figure 4. Schematic of proposed method for measuring treatment impedance using a freefield reflection technique.

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4 Ingard, U. and Bolt, R. H., "A Free Field Method of Measuring the Absorption Coefficient of Acoustic Materials", J. Acous. Soc. Amer., Vol. 23, No. 5, Sept. 1951, pp. 509-516.

5 Allard, J. F. and Champoux, Y., "In Situ Two-Microphone Technique for the Measurement of the Acoustic Surface Impedance of Materials", Noise Control Engineering Journ., Jan-Feb.1989, pp. 15-23.

6 Rogers, C. L. and Watson, R. B., "Determination of Sound Absorption Using a Pulse Technique", J. Acous. Soc. Amer., Vol. 32, No. 12, pp. 1555-1558.

The theory, which uses an assumed value for the surface impedance, is used to predict the pressure signals at the microphone positions, in terms of the cross-spectrum or transfer function value at a specified frequency. When a value of surface impedance is chosen sufficiently close to the actual value, the differences between the prediction and measurement will be a minimum. For simple geometric arrangements and idealized incident wave forms, a solution for the impedance can be put into closed form.

Modern methods of predicting wave propagation above and reflection from surfaces that are not necessarily of uniform impedance (say a patch of uniform impedance surface in an otherwise rigid plane), such as boundary element methods or finite element methods, could be used as the propagation analysis to predict the pressure measured at one or more microphones above the surface. The precise nature of the source distribution or directivity pattern could be included, if necessary. The measured complex pressures could then be used to work backwards through the analysis to determine the impedance that produced the reflected wave.

At high frequencies characteristic of sub-scale acoustic treatment, it is conceivable that the apparatus could be small enough to be located in a non-anechoic laboratory. Questions of uniqueness would have to be considered in determining the number and location of measurement microphones.

Other possible issues for the Free Field Method of measuring acoustic impedance would be:

1. Would like to use the method to measure surface impedance between the frequencies of 13,000 Hz. and 25,000 Hz.
2. Impulse method is worth investigation, but would also like to be able to measure effects of broadband excitation on impedance, both for spectrum shape and SPL level, for nonlinear materials like perforated plate.
3. May measure impedance between 13,000 and 25,000 Hz. only, but may want panel excited by acoustic energy from about 500 Hz. to 25,000 Hz. (or above) to simulate SPL environment in fan ducts. Thus, multiple sources may be needed, some not directly involved in the measurement.
4. Typical SPL spectra for scale model fan ducts could be simulated. Overall SPL's would be on the order of 150 dB.
5. It may be necessary to develop a high-intensity source to get sufficient acoustic energy up to 25,000 Hz.
6. In addition to determining impedance at surface, would like to determine excitation SPL spectrum at surface as part of the measurement.
7. Treatment panels to be measured will be flat, preferably rectangular. One issue will be—what is the minimum size panel from which sufficiently accurate free field impedance measurements can be made? How important are edge effects and can they be accounted for by the analysis technique?

8. Sample panels of scale model fan treatment can be provided, but for method development, a thin sheet of almost any uniform absorptive material may be made into a sample panel.
9. Objective would be to develop a measurement system that could find practical use by trained test technicians, define the specs and measurement procedure. Since this will be a precision measurement rather than a "production" type test, it can be assumed that the testers will have a high level of expertise.
10. Can the measurement be made in a reverberant room environment or does it require an anechoic chamber?
11. May need to develop or find special high-frequency, small diameter sensors (fiber optics?), means of precisely locating the sensors (lasers?), and will need to develop methods for calibrating the system.
12. There may be some materials the impedance of which can be predicted reliably at frequencies up to 25,000 Hz. (NASA Langley is proposing a ceramic material composed of closely-stacked capillary tubes that could be cut to any thickness for this purpose.)

One disadvantage of the method would be the difficulty of performing the measurement in the presence of grazing flow. Larger samples would have to be constructed than for the case of the impedance tube or flow duct, but this would have the advantage of providing a more representative surface.

7. Conclusions and Recommendations for Further Investigation

7.1 Conclusions

Extensive studies of effects of high frequencies and small scales on acoustic treatment panels were completed. An extended frequency impedance prediction model was developed and coded into a FORTRAN computer program. A preliminary model of a time-domain model for nonlinear effects on the impedance of a single-degree-of-freedom (SDOF) resonator covered by a perforated sheet was developed. Effects previously ignored that may result in improved accuracy for full scale impedance models were identified.

The goal of increasing the upper frequency measurement limit for acoustic impedance to above 12,000 Hz. was achieved in the case of no grazing flow, but attempts to measure impedance at high frequencies in the presence of grazing flow were unsuccessful. Analytical impedance prediction models were developed that show excellent correlation with the measured normal incidence impedance up to about 13,000 Hz.

Measurements of DC flow resistance at high temperatures indicate that there is a simple and reliable temperature conversion based on the temperature-dependence of viscosity that can be applied to perforates and wiremesh materials. Measurements of DC flow resistance with grazing flow show expected behavior from perforate and wiremesh materials. Unfortunately, time did not allow more detailed analytical correlation of the DC flow measurement with grazing flow data.

In-duct measurements of acoustic impedance with grazing flow using the two-microphone method were unsuccessful. This was attributed primarily to defects in the instrumented duct test samples used for the measurement, caused by difficulties in fabrication. Although alternative procedures for sample preparation are suggested to improve this method, it is generally concluded that the precision requirements are so stringent that the likelihood of applying the method successfully at higher frequencies and smaller scales is very small.

In-duct transmission loss measurements, with and without grazing flow, met with limited success. The measurements were performed up to Mach 0.8, but difficulty was encountered in attempting to correlate the analytical prediction with the measured data with what would be considered to be adequate agreement. The difficulties are most likely to be attributable to measurement problems in the calibration of the multiple microphone arrays used in the modal decomposition.

A set of guidelines for the utilization of treatment scaling as a full scale engine treatment design tool were recommended. The key to being able to use treatment scaling is the ability to predict and measure acoustic impedance for sub-scale panels accurately up to the highest scaled frequency required. A procedure for incorporating testing of treated scale model fans into the treatment design optimization process has been proposed.

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13. ABSTRACT (Maximum 200 words)

Scale model fan rigs that simulate new generation ultra-high-bypass engines at about 1/5-scale are achieving increased importance as development vehicles for the design of low-noise aircraft engines. Testing at small scale allows the tests to be performed in existing anechoic wind tunnels, which provides an accurate simulation of the important effects of aircraft forward motion on the noise generation. The ability to design, build, and test miniaturized acoustic treatment panels on scale model fan rigs representative of the fullscale engine provides not only a cost-savings, but an opportunity to optimize the treatment by allowing tests of different designs. The primary objective of this study was to develop methods that will allow scale model fan rigs to be successfully used as acoustic treatment design tools. The study focuses on finding methods to extend the upper limit of the frequency range of impedance prediction models and acoustic impedance measurement methods for subscale treatment liner designs, and confirm the predictions by correlation with measured data. This phase of the program had as a goal doubling the upper limit of impedance measurement from 6 kHz to 12 kHz. The program utilizes combined analytical and experimental methods to achieve the objectives.

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It should be recognized that the further methods development required to use scaled treatment as a design tool are specialized to the high frequency requirements of scaling. A degree of precision and care is required in high frequency experiments that is not necessary for testing full scale treatment panels. The high frequency measurement procedures are likely to be costly and exacting, but the developments will have no direct application to full scale treatment design, testing, or analysis, that is, they would not be needed for full scale design were it not for the desire to use sub-scale treatment tests as a design tool.

Before proceeding further, it is necessary to ask whether the added expense of these specialized techniques will be justified by the reduction in cost anticipated by being able to use scale model vehicles for treatment design and development. The cost savings of a scale model test over an equivalent full scale engine test is estimated to be $500K or more, so that further effort in developing the scale model treatment technology is certainly worthy of serious consideration.

7.2 Recommendations for Further Research

Sub-scale treatment testing as a design method will not become possible without adequate methods to predict and measure acoustic impedance at high frequencies. This is essential in order to be able to interpret the results of scale model treatment suppression tests, no matter what the design of the treatment. Further effort must be focused on improving the prediction and measurement of treatment impedance.

The most immediate need for the advancement of treatment scaling methods is the ability to increase the upper limit of frequency range for the measurement of acoustic impedance. A short-term objective would be to double the upper limit to about 25,000 Hz. It is anticipated that non-conventional, specialized methods of impedance measurement will be required to make this measurement accurately and reliably. Three methods are suggested for further investigation, the further miniaturization of the normal incidence impedance tube, the use of miniaturized flow ducts, and the adaptation of the free-field method of impedance measurement to short wavelengths.

Of these methods, the only one that addresses the problem of impedance measurement in the presence of grazing flow is the miniaturized flow duct. Since the possibility exists that there is a frequency-dependence of impedance on grazing flow effects, effort should continue to develop an advanced measurement method.

The time-domain model for predicting nonlinear effects on facesheets shows promise for increased understanding of the fluid dynamic mechanisms that may have effects at high frequencies. It is recommended that further development of this program be continued, particularly to improve the finite difference integration and to incorporate advanced fluid dynamic models in the facesheet lumped impedance.